

ASSESSMENT OF LIQUEFACTION POTENTIAL BY COMPARING SEMI-EMPIRICAL METHODS BASED ON THE CPT TEST

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Abstract

Liquefaction is a dangerous and temporary phenomenon whereby water-saturated soil loses all or part of its strength. Undrained conditions associated with cyclic loading increase water pressure in soil pores, thereby reducing effective stress. The aim of this study is, on the one hand, to report on the phenomenon of liquefaction of sand, clay and silt deposits in more or less water-saturated zones in the section located at the heart of the central alluvial plain of the Oued Sebou in the mio-plio-quadernary Gharb basin and, on the other hand, to study the ability of semi-empirical methods to correctly assess liquefaction potential, while specifying the most appropriate method for the area studied. The study is based on data from experimental results of static penetrometer tests between the Mnasra - Ouelad Salama zone in the Oued Sebou alluvial plain of Morocco's mio-plio-quadernary Gharb basin, made up of sandy, sandy-clay, sandy-silt and silty-sandy formations, which are more sensitive to liquefaction due to their saturation and grain size. We present and discuss the results of Olsen's method, Juang's method and Robertson's method, which are based on the CPT static penetrometer test, as well as looking at the impact of dynamic loading and soil structure on liquefaction probability index values.

Keywords:

Liquefaction;
Cone Penetration Test (CPT);
Semi-Empirical Methods;
Liquefaction probability index;
Earthquake study.

1 Introduction

Liquefaction is a phenomenon that occurs in saturated soils when they are subjected to a sufficiently intense cyclic dynamic action, such as that generated by a major earthquake. Non-draining conditions within the soil increase pore pressure to such an extent that it can compensate for total stresses by making effective stresses disappear, and the soil then behaves like a liquid and no longer takes up shear forces [1].

As part of the construction of the high-speed rail link between Casablanca and Tangiers, which passes through the Mnasra and Oulad Salam regions, and with the aim of building a railway bridge over the Oued Sebou (Figure 1), Geotechnical studies were carried out to assess the risk of liquefaction in this locality, which is exposed to flooding and has a high water table, while being characterized by sandy, silty and clayey formations that are potentially vulnerable to the liquefaction phenomenon [2]. The area concerned belongs to the Sebou sub-basin in eastern Morocco, part of the greater Gharb basin. Its boundaries are the Prérif to the north and east, the Moroccan Meseta to the south and southwest, and the Atlantic Ocean to the west. This region belongs to a subsidence zone with mio-plio-quadernary filling [3-5]. the Quadernary. The Mnasra area is largely covered by Soltanian marine sand and sandstone formations (equivalent to Weichselian) [3]. These deposits, which make up the bulk of the surface formations in the Mnasra area, evolve along the banks of the Oued Sebou, where they are represented by continental deposits of clayey or silty alluvium from the Gharbien (equivalent to the recent Holocene) [3-6].

The aim of this study is to evaluate the effectiveness of three liquefaction evaluation procedures (LEP) liquefaction evaluation procedures (LEP) based on the cone penetration test (CPT), operating within a liquefaction potential index (LPI) framework, in predicting the severity of surface liquefaction manifestation, which is commonly used as an indicator of liquefaction-related damage potential [7-9].

Using geological, geotechnical, and seismic data to assess the liquefaction susceptibility of boreholes drilled as part of this project, located more precisely between KP 183+000 and KP 185+900. The semi-empirical methods used in this study are part of the cyclic stress approach, three of which are based on CPT static penetrometer test data, namely Olsen's method [10], Juang's method [7] and Robertson & Wride's method [11]. Each method presents a mathematical model based on hundreds of historical cases and experimental data from liquefiable and non-liquefiable sites. They also reflect the soil's capacity to resist cyclic shear pressures and are mainly based on relative density, grain size, soil texture, saturation level and earthquake magnitude.

The calculation of the Liquefaction Probability Index (LPI) predicts that liquefaction is confirmed by all three methods on the Oued Sebou alluvial plain, with spatial-temporal variations, particularly for boreholes on the Oued Sebou periphery, given the degree of saturation, grain size and nature of the formations, which are not compact at certain depths.

2 Regional data

2.1 Geological Framework

The plio-villafranchian trays around Selouane, which depend on the volcanic rocks of Bni-Bou - Ifrou and Laglab, divide the Gharb basin, an elongated WSW-ENE basin, from the Bou-Aregplain. A wide pass at the west offers access to the Oued Kerte basin, which is located south of the plain-closing Jbel Tistoutine and Jbel Bni-Bou-Ifrou [4, 5, 12].

Greyblue marls crossing at Pliocene without changing any of their features are a representation of the Upper Marine Miocene. Because of the haziness of the relationships between the Miocene and Pliocene, identical Pliocene deposits can be mistaken for the lagoon-continental deposits from the transition between these two phases.

In the Villafranchien lacustrine event, white to yellowish limestones were developed, which passed both horizontally and vertically to sublithographic limestones, tuffeous and chalky limestones, or nodular marlcalcareous. These limestone facies in the SE and NE areas of Gareb transition laterally to weakly consolidated conglomerates with clay cement or to well consolidated conglomerates, whose constituents are frequently volcanic in origin. These lacustrine strata occasionally have gravel and pebble silt intercalations [4, 5, 12].

The mid Quaternary formations, which are fine and red formations attributed to the Amirien and end in tennsiftien crusting, are visible above this Villafranchien. Red to pink clay silts that are calcareous make up the Amirian. The Tennsifien is depicted as a white, highly calcareous tuff that is covered in a thin, laminated, nodular crust [4, 5, 12].

Finally, a small layer of red to brown silts represents the recent Quaternary, which is seen practically everywhere.

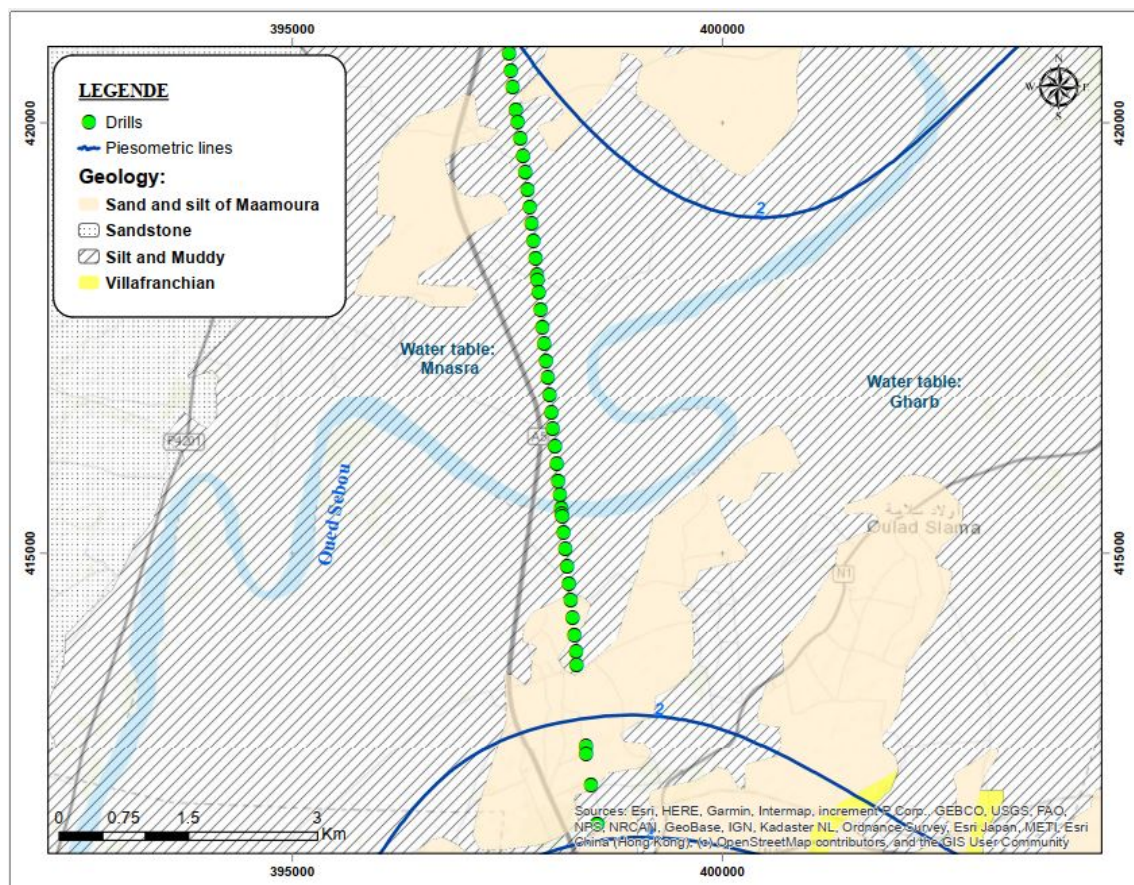


Fig. 1: Geological map of the Gharb basin [13].

2.2 Hydrogeological Framework

According to [12, 14], depending on the region, the impermeable foundation of groundwater is made up of two different units. These are either blue-gray marine marls from the base of the Pliocene or Upper Miocene, or colorful marls, sometimes containing pebbles, that can be dated to the Pontico-Pliocene.

However, the impermeable level is found in the Quaternary to the southwest of the plain, where drilling has only reached pebble silts before encountering the detritic limestone of the lower Miocene at a depth of 219 m. In several drill holes, the impermeable horizon was discovered above the mio-pliocene formations [14].

In the southwest of the plain, lacustrine deposits of Villafranchien and silts with pebbles and gravel predominate. The impermeable horizon occasionally can be found in the lake levels of Villafranchien, and it has a lenticular structure [12, 14].

The iso-piezometric curves map (Figure 1) reveals that the flow of groundwater is directed from the SW and S towards the NE, where it contributes to the groundwater used by the Bou-Areg plain [14].

2.2 Study area

A sandy horizon 2 to 8 meters thick was discovered during this soil investigation using the Cone Penetration Test (CPT). In addition, on-site analyses of the sandy-clay-loam material showed that it had poor mechanical qualities, classifying it as loose sand. According to tests conducted between 2007 and 2009, the water table can be found between 2.80 and 6.0 meters deep. Different conversion laws between magnitude and intensity were developed by Cherkaoui [15], allowing to relate these two quantities considering the lithology of the land and its granulometry, which are in the range of liquefiable soils. The RPS 2011 [2] indicates that the maximum amplitude of horizontal acceleration around Oued Sebou, located in the seismic zone 3, is 0.14 g.

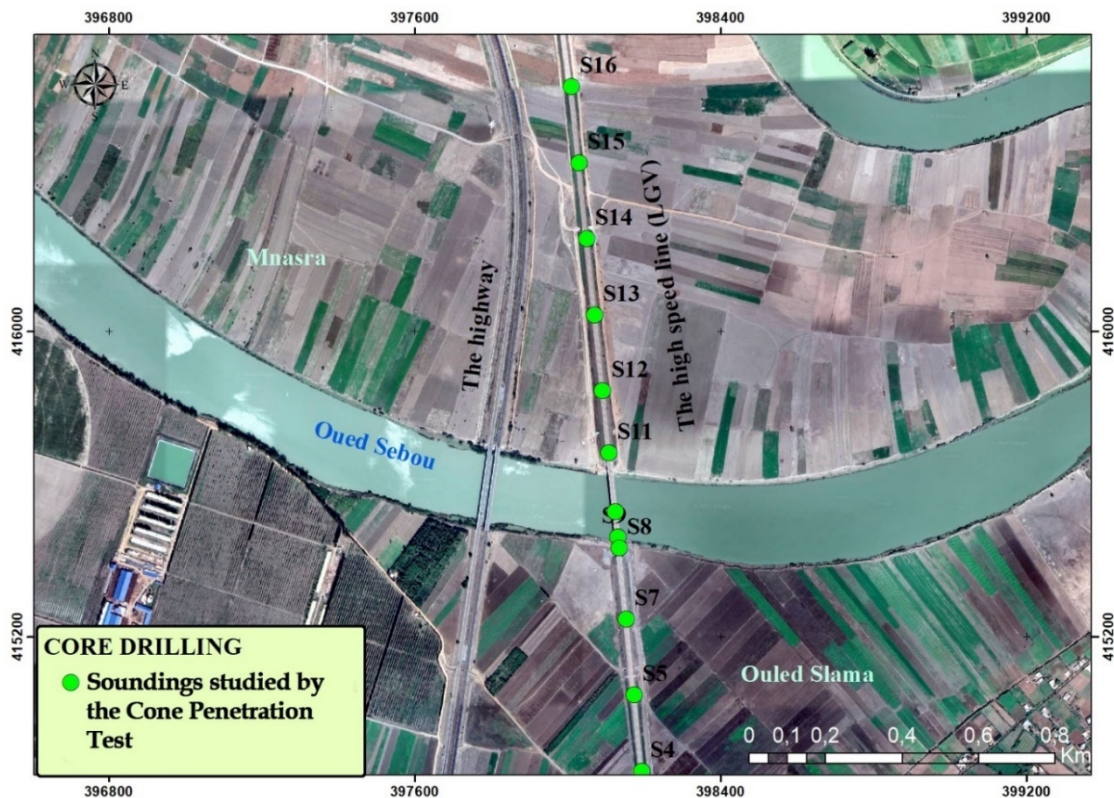


Fig. 2: Geographical location of the study area, with the different cores taken from the alluvial plain of Oued Sebou along the high-speed line.

3 Methodology

Several types of tests have been developed to assimilate the liquefaction phenomenon and help identify sites with a tendency to liquefy. In this manuscript, we based our research primarily on the in-situ Cone Penetration Test (CPT). With this in mind, and with the aim of assessing the liquefaction potential of the Oued Sebou alluvial plain, several drills were drilled along the high-speed line (LGV), as illustrated in Figure 2 above.

These static penetrometer tests (CPT) were carried out as part of this project, with the aim of accurately assessing the liquefaction potential along the section (Fig. 2) studied and obtaining conclusive results. Thanks to this test, we can determine two parameters essential to the calculation of Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR), by means of which we can determine the safety factor F_s :

The tip resistance q_c represents the ratio between the force measured on the cone tip Q_c and the area of the normal projection surface of the cone tip A_c .

The local lateral friction f_s represents the ratio between the friction force on the sleeve F_s and the area of its surface A_s .

From the tip resistance determined as a function of depth, we can determine whether the soil is potentially susceptible to liquefaction or not (Fig.3) as a preliminary study, without having to enter into the tedious calculation of the liquefaction probability index (LPI). As a result, and to filter out the large amount of data, we treated all boreholes according to the following rule of thumb: geological formations with a peak resistance q_c of the order of 5000 kPa and above, meaning that the effective stress is very large compared to the pore pressure, suggesting that the soil is compact and not dense enough to be susceptible to liquefaction [16].

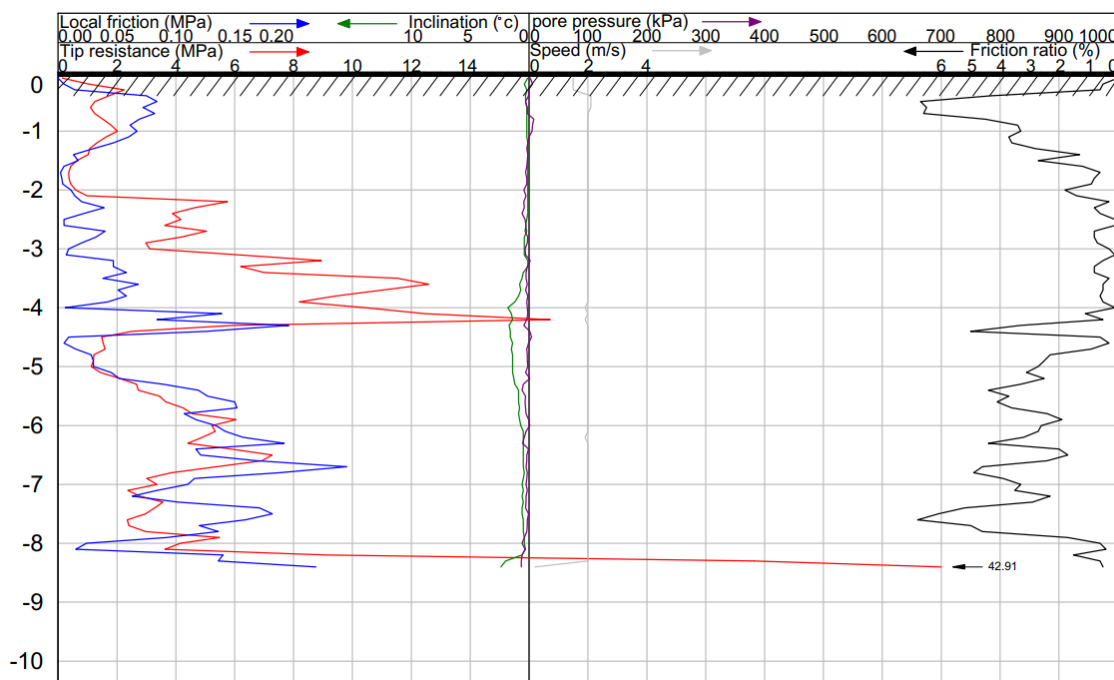


Fig. 3: Variation of peak resistance q_c and local lateral friction as a function of depth.

Also, in this data processing, we took into consideration soils that are a priori susceptible to liquefaction according to [2], as well as parameters determining soil liquefaction such as: Relative density, granulometry, soil texture, saturation level and earthquake magnitude all have a significant impact on this potential, which measures soil resistance to cyclic shear forces.

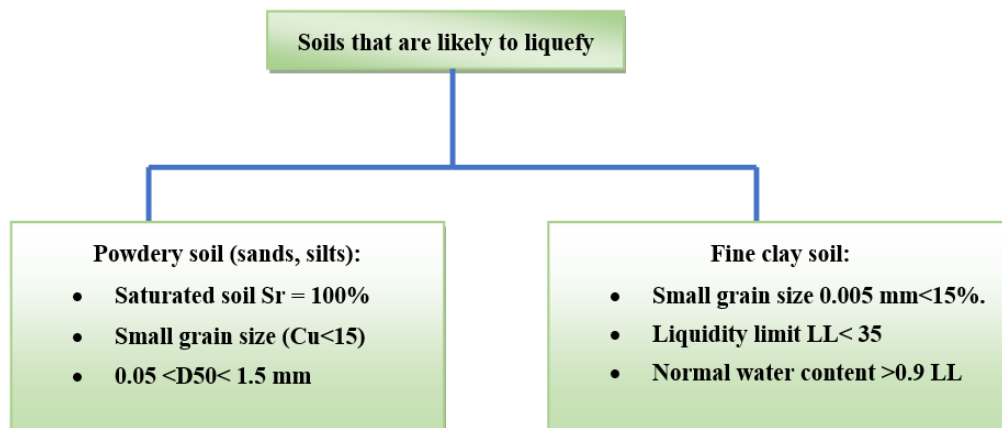


Fig. 4: Soils susceptible to liquefaction [2].

Figure 5 reveals that the clay soils in this region are potentially liquefiable, as most samples show low plasticity.

Semi-empirical methods for quantifying liquefaction potential were invented by scientists and are based on the results of field tests (in our case, the CPT static penetrometer test), liquefaction effects and previous seismic studies. They can be divided into three different types of approach:

- The energy approach [1];
- The cyclic deformation method [9];
- The cyclic strain method [7-9].

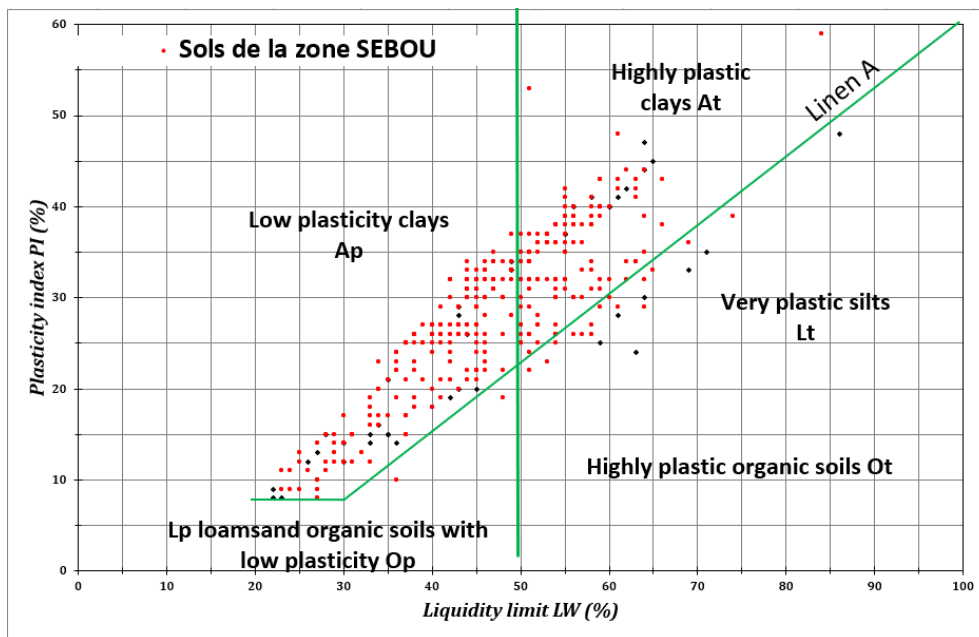


Fig. 5: Liquidity limit and plasticity of the Oued Sebou alluvial soil. (*The red dots represent drill holes located at a distance from Oued Sebou with a very low to possible liquefaction potential. **The black dots represent drill holes located near Oued Sebou with a liquefaction potential ranging from weak to certain.)

The cyclic stress approach is the one that is most frequently employed in practice to assess the resistance of soils to liquefaction for the determination of a factor of safety (FS) [1][17]. The FS is calculated as the product of the cyclic strength CRR and the cyclic stress CSR.

The evaluation techniques that are suggested in this study are based on the CPT in-situ test data and the cyclic stress methodology.

3.1 Evaluation of the cyclic stress ratio (CSR)

Based on the condensed technique developed by Seed and Idriss [1], who provided the following connection [17], [18], the estimation of CSR for the three methods under study is as follows:

$$CSR = \frac{\tau_{av}}{\sigma'_{v0}} = 0,65 \left(\frac{a_{max}}{g} \right) \left(\frac{\sigma_{v0}}{\sigma'_{v0}} \right) r_d \quad (1)$$

where:

τ_{av} – the average cyclic shear stress in (kPa),

σ'_{v0} – effective vertical stress in (kPa),

a_{max} – l'amplitude maximale de l'accélération horizontale (m/s²),

g – 9,81 m/s² is the acceleration of gravity,

σ_{v0} – is the total vertical stress due to the weight of the overlying soils (kPa),

r_d – A stress reduction coefficient that reflects the flexibility of the soil column in (m).

As a function of depth, the following equations represent the stress reduction coefficient[17-19]:

$$r_d = 1 - 0,00765 Si Z \leq 9,15m \quad (2-a)$$

$$r_d = 1 - 0,00765 Si 9,15m \leq Z \leq 23m \quad (2-b)$$

Equation (1) is used in the Juang method [7] to calculate the CSR, and the MSF coefficient was added to the equation to adapt the CSR value to a magnitude 7.5 earthquake. Equation (1) is changed to:

$$CSR = \frac{\tau_{av}}{\sigma'_{v0}} = 0,65 \left(\frac{a_{max}}{g} \right) \left(\frac{\sigma_{v0}}{\sigma'_{v0}} \right) \frac{r_d}{MSF} \quad (3)$$

where MSF is expressed by equation (4) according to [20]:

$$MSF = 10^{2,24} / M_{W^{2,56}} = \left(\frac{M_w}{7,5}\right)^{-2,56} \quad (4)$$

where:

MSF – is the magnitude scaling factor (SI),

M_w – is the magnitude of the earthquake.

The evaluation of the CRR in this study is based on data from the CPT test, which is among the most common in-situ tests in Morocco.

3.2 Semi-empirical methods

1) Olsen's method

Based on the investigation of numerous factors influencing soil liquefaction, Olsen simplified the estimation of the CRR using equation (5):

$$CRR = 0,00128 \left(\frac{q_c}{\sigma'_{v0}}\right)^{0,7} - 0,025 + 0,17R_f - 0,028R_f^2 + 0,0016R_f^3 \quad (5)$$

With R_f is (friction ratio), a percentage expressed as follows:

$$R_f = \frac{f_s}{q_c} \times 100 \quad (6)$$

The Olsen method does not have a clear physical component for determining the CRR. Except for depths larger than 10 m, it is simple to use but does not anticipate all the sites likely to liquefy in the same way as the other two approaches. As a result, it is less trustworthy than the other two techniques. Additionally, Olsen's approach [8].

2) Juang's method

For the Juang method, the CRR is expressed by [7] [6]:

$$CRR = C_\sigma \exp \left[-2,957 + 1,264 \left(\frac{q_{c1N,cs}}{100} \right)^{1,25} \right] \quad (7)$$

with:

C_σ – expressed in (kPa),

q_{c1N} – is the tip strength q_c of the cone adjusted for stress,

$$C_\sigma = -0,016 \left(\frac{\sigma'_{v0}}{100} \right)^2 + 0,178 \left(\frac{\sigma'_{v0}}{100} \right)^2 - 0,063 \left(\frac{\sigma'_{v0}}{100} \right) + 0,903 \quad (8)$$

$$q_{c1N,cs} = K_I q_{c1N} \quad (9)$$

$$K_I = 2,249(I_c)^4 - 16,943(I_c)^2 - 51,497(I_c) + 22,802 \quad (10)$$

K_I – is an intermediate parameter that was part of the regression process (Juang and al.),

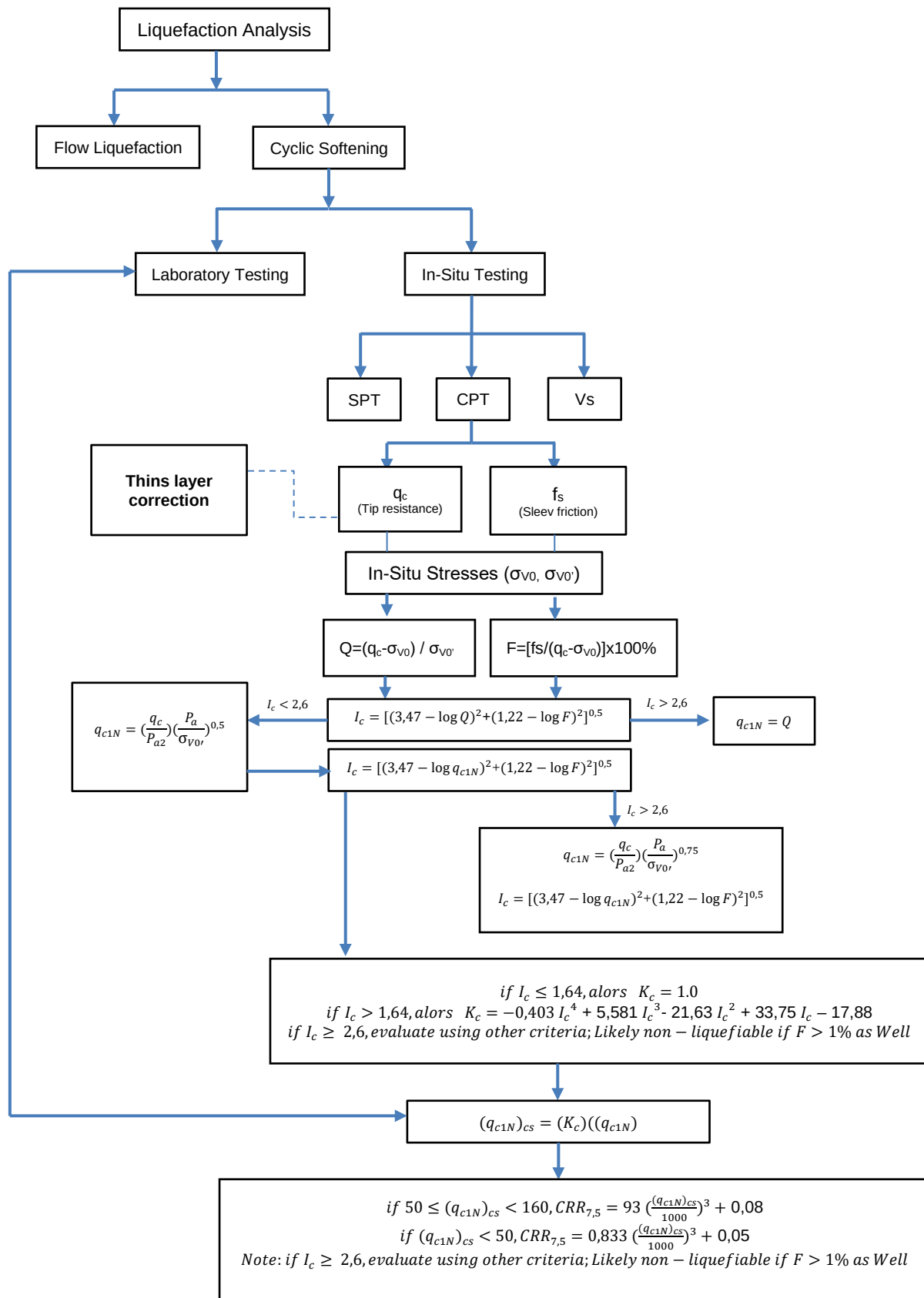
$$I_c = [(3,47 - \log_{10}(q_{c1N}) + (\log_{10} F + 1,22)^2)^{0,5}] \quad (11)$$

I_c – is a variable defined according to [16]. F is the normalized friction ratio defined as follows:

$$F = \frac{f_s}{(q_c - \sigma_v)} \times 100 \quad (12)$$

3) Robertson and Wride's method

Robertson and Wride's Cyclic Resistance Coefficient (CRR) evaluation method is defined as follows [9, 20]:



3.2 Evaluation of the safety coefficient and the probability of liquefaction

The safety factor is expressed by the same equation for all methods based on the cyclic stress approach [17]:

$$F_s = CRR / CSR \quad (13)$$

From the safety factor, the probability of liquefaction can be determined [7]:

$$IPL = \frac{1}{1 + \left(\frac{F_s}{A} \right)^B} \quad (14)$$

where:

- A = 1 and B = 2.78 according to the Olsen method;
- A = 0.96 and B = 4.50 according to the Juang method;
- A = 1 and B = 3.30 according to the Robertson and Wride method.

From the probability index defined by equation (14), the class of occurrence of liquefaction (Table 1) [7-9].

Table 1: Occurrence of liquefaction by probability index [7].

IPL	CLASSE	DESCRIPTION (PROBABILITY OF LIQUEFACTION)
$IPL \geq 0,85$	5	Liquefaction almost certain
$0,65 \leq IPL < 0,85$	4	Liquefaction very likely
$0,35 \leq IPL < 0,65$	3	Liquefaction and no-liquefaction are possible
$0,15 \leq IPL < 0,35$	2	Liquefaction unlikely
$IPL < 0,15$	1	Liquefaction almost impossible

4 Results and discussion

4.1 Results

Calculation of the IPL by the semi-empirical p methods adopted for this study (the example of boreholes S7 and S11, Tables 2 and 3) ranges from 0.66 to 0.98, indicating a very high risk of liquefaction in sandy and silty formations, particularly silty-clay and silty-sandy formations. As liquefaction potential increases with depth (Figure 7), it should be noted that liquefaction is unlikely to occur at depths below 8 m for boreholes S5, S7 and S9. With increasing depth, the likelihood of liquefaction increases to the point of certainty for boreholes S7, S9 and S11 and S12, due to the sandy, sometimes silty and silty-clayey formation, which perfectly meets the liquefaction criterion in the presence of groundwater. Slices of sediments showing definite liquefaction range from 8 m to 20 m for borehole S7, 12 m to 22 m for borehole S9, 13 m to 18 m for borehole S11 and, finally, from 4 m to 6 m and 14 m to 16 m for borehole S12. At depths of over 22 m, the formation becomes more compact, and with the absence of a water table, the risk of liquefaction diminishes.

Table 2: Results of the liquefaction probability index by the methods of Olsen, Roberston and Juang.

S	Lithology of the terrain	Depht (m)	IPL by Olsen	IPL by Robertson	IPL by Juang
S7	Mudd	0-2	0,07	0,11	0,07
	Silty-Clays	2-4	0,09	0,16	0,10
		4-6	0,15	0,27	0,16
		6-8	0,35	0,47	0,41
		8-10	0,36	0,48	0,43
		10-12	0,38	0,49	0,45
	Sandy-Silt Sandy-Clay	12-14	0,55	0,66	0,65
		14-16	0,57	0,71	0,66
		16-18	0,57	0,71	0,67
		18-20	0,63	0,76	0,73
		20-22	0,67	0,95	0,77
		22-24	0,68	0,98	0,78
		24-26	0,69	0,82	0,79
	Sandstone	26-30	0,05	0,12	0,00

Table 3: Results of the liquefaction probability index by the methods of Olsen, Roberston and Juang.

S	Lithology of the terrain	Depht (m)	IPL by Olsen	IPL by Robertson	IPL by Juang
S11	Clayey	0-2	0,00	0,08	0,00
	Silty-Sand	2-4	0,002	0,21	0,10
		4-6	0,006	0,23	0,11
		6-8	0,056	0,23	0,13
		8-10	0,057	0,29	0,17
		10-12	0,062	0,31	0,20
	Fine-Sand	12-14	0,070	0,31	0,20
		14-16	0,25	0,75	0,41
		16-18	0,53	0,83	0,66
		18-20	0,62	0,89	0,73
		20-22	0,71	0,94	0,77
		22-24	0,61	0,51	0,44
		24-26	0,63	0,52	0,35
	Clay	26-30	0,63	0,52	0,31

Schematically, sediment slices showing very probable liquefaction and certain liquefaction are highlighted in the deposits of the Oued Sebou alluvial plain and its northern edge in the Mnasra region. The sediments in this area, consisting mainly of sands and silts, often clayey-silty or silty, located at depths of 0 m and 22 m, have a very probable and even certain liquefaction potential, while excluding the clayey-sandy level located between m and m, which presents an unlikely liquefaction; whereas in the center of the Oued Sebou alluvial plain, liquefaction is determined at depths of 8 m and 12 m respectively at drillings S7 and S9. These results demonstrate that grain shape (silt and sand) in the presence of groundwater increases the probability of liquefaction, as indicated in the methods and materials section of RPS 2011 [2].

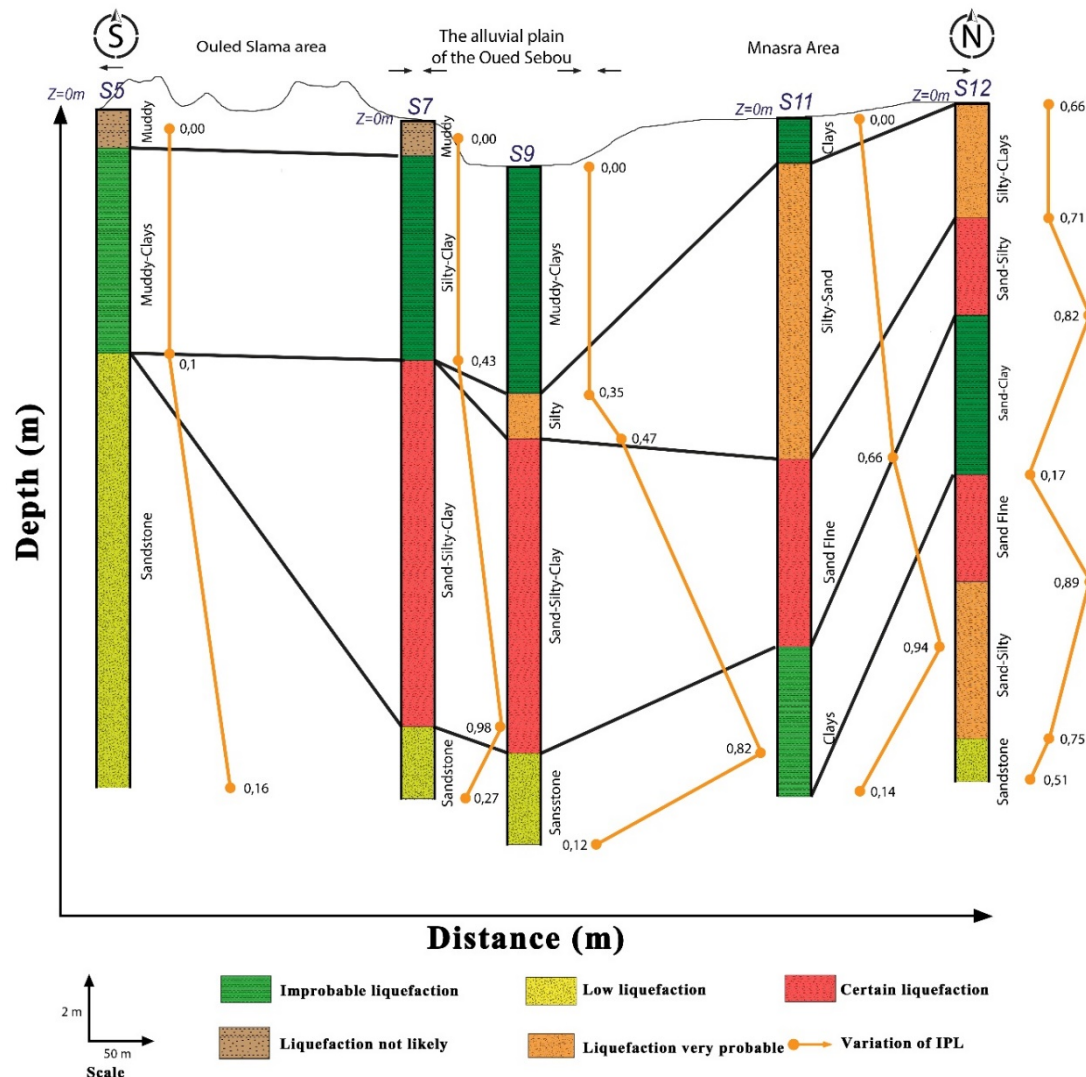


Fig. 7: Correlation of sedimentary deposits in liquefiable layers as a function of depth in drill holes S5, S7, S9, S11 and S12, located on the edge of the Oued Sebou alluvial plain and most affected by the railway bridge project: Variations in the liquefaction probability index (LPI) indicate the liquefaction potential for each layer in accordance with Table 1, showing that clay and silty layers are equally susceptible to liquefaction when the conditions cited in Figures 4 and 5 are verified [7, 9].

4.2 Discussion

The three methods presented in this article are all cyclic stress approaches based on CPT test data. Data from boreholes from KP 185+000 (S5) to KP 184+200 (S12) were processed to better understand the fluctuation of the liquefaction probability index as a function of lithology, saturation levels and magnitude, as these boreholes present moderately different layers, which has some impact on the cyclic strength calculation (CRR) and, consequently, on the safety coefficient used in the liquefaction index calculation.

Figures 8 and 9 show the safety factor results obtained for the cases of KP 184+800 (S11) and KP 185+200 (S7), respectively, where we highlight the presence of points with safety factors lower than 1 and therefore susceptible to liquefaction. Based on these figures, we also observe that the variation of the safety factor curves of the Juang and Robertson methods is almost similar, and that the difference between the two curves of each profile is mainly due to the introduction of the MSF factor in the CSR calculation. Over certain depth ranges, we find that Olsen's F_s curve and Robertson's curve are almost merged, particularly when they exceed 12 m in depth [21, 22].

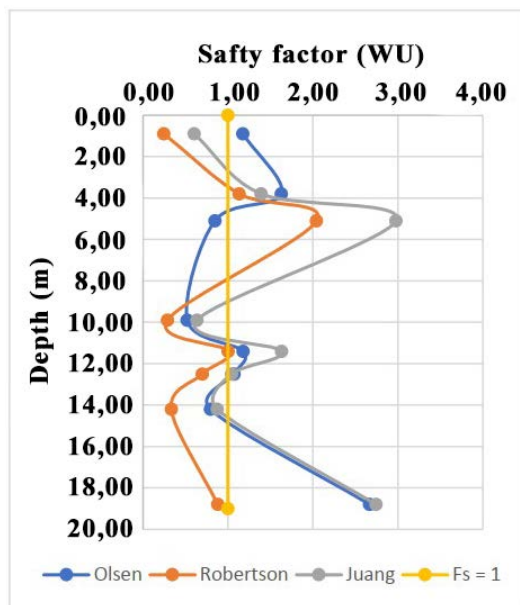


Fig. 8: Safety factor (Fs) values of the three methods – Case of KP 184+800.

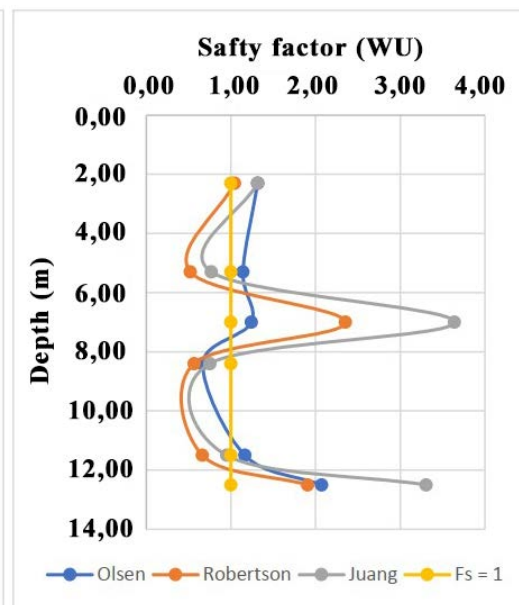


Fig. 9: Safety factor (Fs) values of the three methods – Case of KP 185+200.

These safety factor results are directly reflected in the probability index curves (Figures 10 and 11). As the coefficients A and B vary from method to method (paragraph 3.3), the shapes of the IPL probability curves are slightly offset from the Fs safety factor curves. Olsen's [8] approach to calculating the CRR is characterized by the absence of a well-defined physical aspect. Except for depths greater than 10 m, it does not anticipate all the points likely to liquefy in the same way as the other two approaches. Consequently, it is less reliable than the other two approaches. What's more, Olsen's method includes an R_f term that regularizes the CRR curve, and hence the safety coefficient, giving us results that don't correspond to practice [21-23].

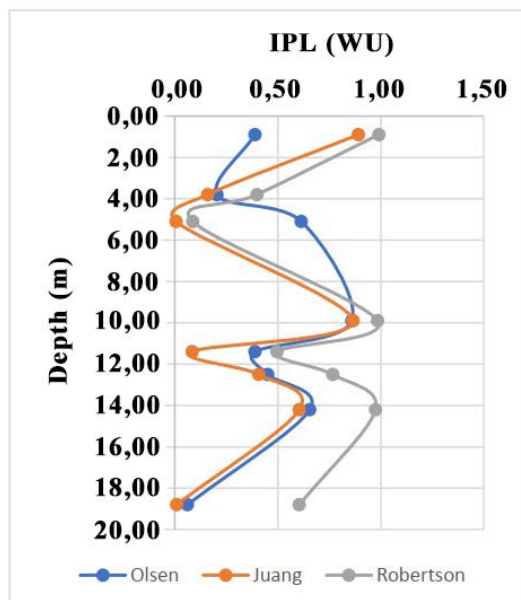


Fig. 10: Liquefaction Probability Index (IPL) values of the three methods – Case of KP 184+800.

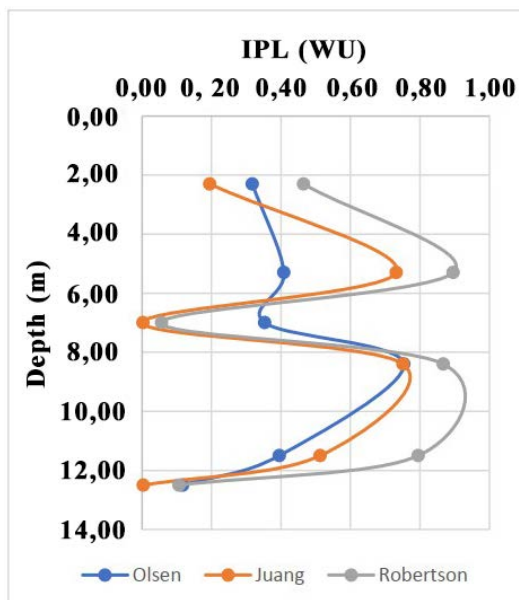


Fig. 11: Liquefaction Probability Index (IPL) values of the three methods – Case of KP 185+200.

The adjusted qc_{1N} values determined by the Juang [7] and Robertson [9], [20] approaches are virtually identical, but there is disagreement for the $qc_{1N,cs}$ values (Figures 12 and 13).

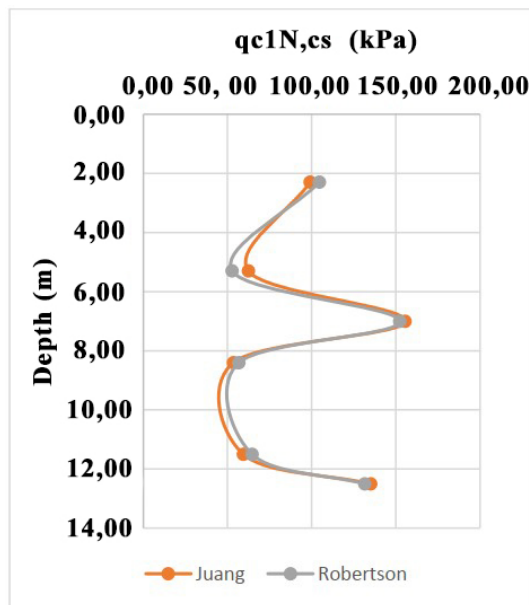


Fig. 12: Values of the $q_{c1N,cs}$ of the method Juang's method and the Robertson method.

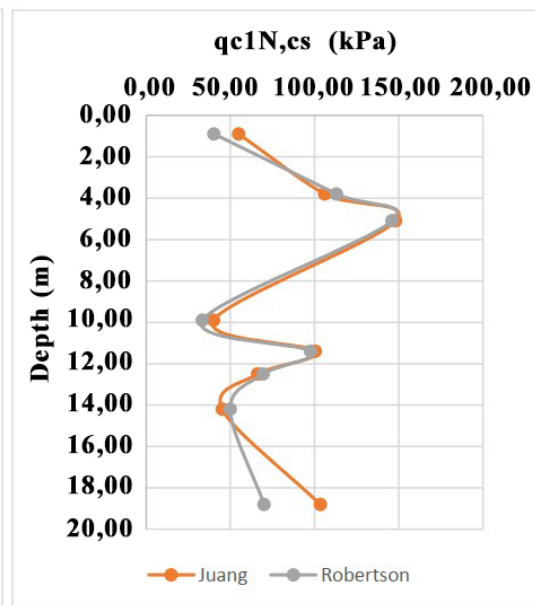


Fig. 13: Values of the $q_{c1N,cs}$ of the method Juang's method and the Robertson method.

After analyzing the IPL results by fluctuating the magnitude up to $M_w = 7.1$, we could see that Juang's approach [7], which is based on a very robust physics aspect and in which Juang used a formulation based on artificial neural networks during its development, seems to be the best compromise for determining the liquefaction potential in this study. It is safe and less sensitive to uncertainties that can impact soil properties [21, 22]. Compared with Robertson's method, which calculates the CRR on $q_{c1N,cs}$, the latter is only valid for clean sand, whereas layers are generally made up of a mixture of silt, clay, silt and sand [21, 22].

Then, we used Quake / W software to model the elements we had gathered. Quake / W addresses the liquefaction issue by employing an initial in situ stress analysis and a dynamic analysis based on the maximum horizontal acceleration recorded at 500 paces by the geophysical station in the Gharb area. [24]. To verify if the outcomes they provided aligned with the ones we had acquired through Juang's technique [7].

We established X boundary conditions in the left and right bounds and XY boundary conditions in the lower boundary for the first in-situ stress study. We established XY boundary conditions in the lower boundary and Y boundary conditions in the left and right borders for the dynamic analysis.

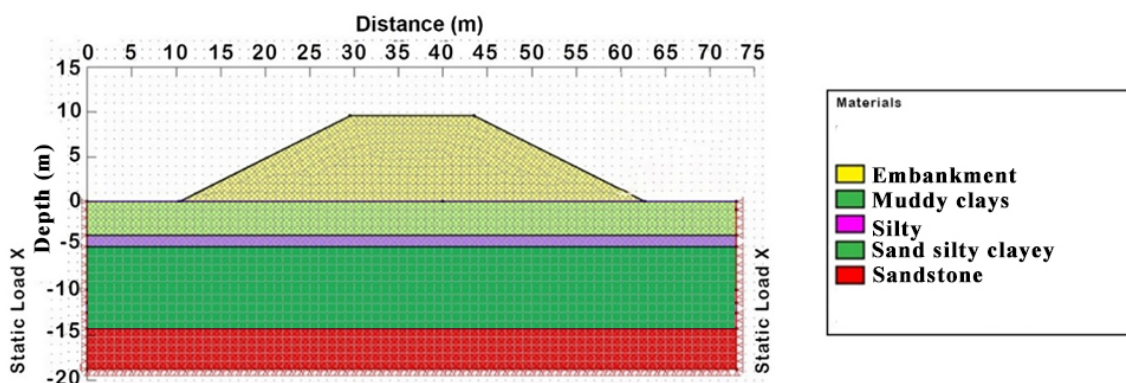


Fig. 14: Dynamic modelling of the layers in drill S9: 1m mesh in accordance with the software user manual, providing a very good data structure [24].

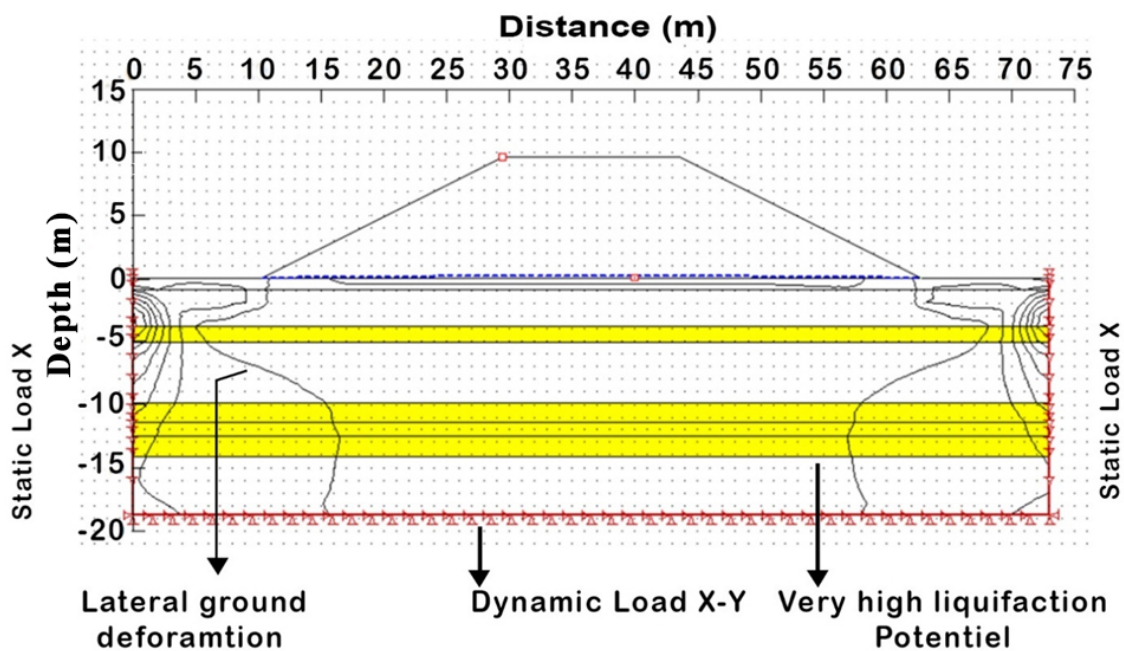


Fig. 15: The liquefiable layers of drill hole S9 are consistent with the calculations carried out and as shown in figure 7: The lateral deformation revealed by the dynamic modelling confirms the certain probability of liquefaction proven by the calculation of the Liquefaction Probability Index (IPL) at the aforementioned drill hole, and suggests that an in-depth study is required for the foundations to be put in place for the bridge [24].

From the base data, we first determined the different material properties for each layer with a dynamic load of $M_w = 7.1$, which was recently recorded in the province of Al House in Morocco.

he results of modeling the two profiles show that:

The two levels of silty sand to sandy silt and silty sand to clayey sand are the most exposed to liquefaction, while the rest of the layers, apart from the clayey or organic layers, are moderately exposed. This demonstrates, on the one hand, the results obtained by Juang's method and the interpretation of the IPL as a function of the layers, and on the other hand, that clayey soils are potentially liquefiable in the same way as sands and silts.

The liquefiable layers are generally located between 6 and 14 m (presence of the water table), which confirms the results of the preliminary analysis of the semi-empirical methods except that for the fine clayey or sensitive silt layer, the pore water pressure is average.

Consequently, and following the results obtained, it should be noted that the physics characteristics of soils (plasticity, liquidity and granulometry) have a major impact on liquefaction even for a magnitude $M_w = 5.7$ on the Richter scale, all safety measures must be taken to protect against this phenomenon, which can cause terrible and catastrophic damage, especially when the magnitude exceeds $M_w = 7$, despite the fact that the area is not known for seismic movements, as in the case of the Al Houz province, and whatever the soil structure, liquefaction probability calculations must be included in deep foundation calculations in the near future.

5 Conclusions

The mio-plio-quaternary Gharb basin contains the deposits of the Oued Sebou alluvial plain, which were the subject of the study. These deposits are made up of sands, alluvium, silts and clays whose grain size meets the requirements and criteria of liquefiable soils, as well as the presence of the water table.

The study focuses on the geological, hydrogeological, seismic, and geotechnical variables affecting liquefaction in the Oued Sebou alluvial plain, as well as their probabilities and spatio-temporal variations.

The tests carried out and the calculation of the IPL using semi-empirical methods showed the existence of a sandy horizon with a thickness varying from 2 to 8 meters. In addition, in situ studies of the sandy-clayey-loamy material revealed mediocre mechanical properties, classifying it as loose sand.

The calculated IPL of 0.66 to 0.98 indicates that there is a very high risk of liquefaction in the predominantly clayey-silty sand formations. The absence of a water table and the granulometry of the sediments that produce the sandstone mean that the IPL becomes zero as depth increases to 22 m and beyond.

The results of these safety factors are directly reflected in the probability index curves. The Olsen approach to calculating the CRR is characterized by the absence of a well-defined physical aspect. As a result, it is less reliable than the other two approaches. The IPL results also show that Juang's approach, which is based on a very robust physical aspect and in which Juang used a formulation based on artificial neural networks during its development, seems to be the best compromise for determining the liquefaction potential in this study. It is safe and less sensitive to uncertainties that may have an impact on soil properties.

This article's three CPT-based techniques are all capable of precisely predicting liquefaction under dynamic loads. However, when evaluating the liquefaction resistance of moderately dense to dense soils, the Juang approach works better.

Numerical modelling confirms the assumptions drawn from the semi-empirical IPL calculation, namely that sandy and silty soils are highly susceptible to liquefaction, and that clay soils are also potentially liquefiable in the same way. As far as geotechnical engineers are concerned, in many projects we apply the rule that if the water table does not exist and the project area is not classified as a seismic zone, we eliminate the likelihood of liquefaction altogether. In theory, however, we can't base our calculations solely on classifications; we must introduce the calculation of liquefaction potential into a posteriori geotechnical calculation, particularly for large projects located close to an alluvial plain, in order to avoid terrible economic and human damage.

In the end, it was decided to opt for the Juang model as an effective method for calculating liquefaction potential.

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